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BIOMECHANICAL BEHAVIOUR OF BOVINE SKIN: AN EXPERIMENT-THEORY INTEGRATION AND FINITE ELEMENT SIMULATION

Nor Fazli Adull Manan*, Jamaluddin Mahmud, Aidah Jumahat

Faculty of Mechanical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

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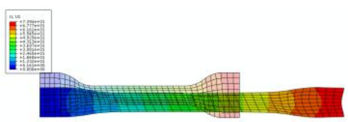
*Corresponding author
norfazli@salam.uitm.edu.my

Graphical abstract



Abstract

This paper for the first time attempts to establish the biomechanical characteristics of bovine skin via experiment-theory integration and finite element simulation. 30 specimens prepared from fresh slaughtered bovine were uniaxially stretched in-vitro using tensile tests machine. The experimental raw data are then input into a Matlab programme, which quantified the hyperelastic parameters based on Ogden constitutive equation. It is found that the Ogden coefficient and exponent for bovine skin are μ = 0.017 MPa and α = 11.049 respectively. For comparison of results, the quantified Ogden parameters are then input into a simple but robust finite element model, which is developed to replicate the experimental setup and simulate the deformation of the bovine skin. Results from experiment-theory integration and finite element simulation are compared. It is found that the stress-stretch curves are close to one another. The results and finding prove that the current study is significant and has contributed to knowledge enhancement about the deformation behaviour of bovine skin.

Keywords: Bovine skin, hyperelastic, ogden model, tensile test, mechanical properties

1.0 INTRODUCTION

The importance of understanding skin behaviour, either in biological domain or engineering field has led to many research. Research to investigate the anisotropic and viscoelastic behaviour were carried out on human, animal or synthetic skin. However there is still limited number of studies conducted on bovine skin, despite its various applications such as accessories (bag, wallet, shoes, etc), clothing, musical instrument (drum) and food. Therefore, advanced study about bovine skin is important; as it could further improve its application for future use.

In general, skin is formed from layers of tissues; namely epidermis, dermis and subcutaneous layer. The main functions of skin include providing natural barriers against infection (protection) and keeping body warm with hair follicles [1]. Some research reported skin a heterogeneous material due to its collagen and elastin fiber composition [2]. Skin complex structure allows it to serve multifunctions [3]. Skin has also been assumed to be semi-infinite layer with isotropic linear elastic [4]. Yet, most research found that skin mechanical behaviour are highly non-linear, anisotropic and viscoelastic [5-7].

For skin research, a wide range of samples have been employed. The investigations and analyses involve human skin, animals and also composite membrane tissues. Samples for studying human skin [8-12]are conducted from various parts and location of human body, such as abdomen, volar and dorsal forearm, cheek and hand, foot skin and back of the hand. Where else, for animal skin, studies have been performed on swine, murine, bovine, rabbit and horse [6, 13-16]. Other than that, some composite materials were exploited in order to investigate their mechanical behaviour which are related to skin behaviour. The materials that could represents skin behaviour include silicone composite, agar-agar, hydrogel, chitosan and collagen, cell-derived matrix-CDM and porous scaffold with silk fiber [17-21].

In terms of theoretical analyses, the biomechanical properties of the complex behaviour of skin has been investigated and determined employing several theories. The most commonly theories employed were Ogden, Mooney-Rivlin, Neo-Hookean, Green theoreom and etc [22-25], which related to hyperelastic and non-linear behaviour. For this study however, only Ogden constitutive model is employed suits to the currently available Matlab programme and commercial finite element software.

In terms of testing and experimental approaches, a number of experimental works has been conducted for skin research, involving in-vivo and in-vitro tests. In brief, in-vivo test refers to in-situ experimental study where the samples are tested directly its parent body, i.e. directly in-situ on human or animal body. In contrast, in-vitro test refers to testing samples detached from its parent body. In-vitro means laboratory works which is it done in controlled area i.e. medical or science lab and all the specimens used normally prepared according to standard or procedure (i.e. excised from main part). An example research related to in-vivo tests [26] includes testing on human skin employing indention in order to investigate skin response and parameters. One of latest in-vivo studies performed on human was to characterise the mechanical properties of facial skin [27, 28]. There has one article from Pharmaceutical journal also discussing the in-vivo study of hairless rats [29]. Other than conventional mechanical tests, modern measuring method such as Motion Capture system has also been developed to measure skin deformation[30].

In-vitro tests have also been conducted vigorously to investigate skin behaviour, either carried-out according to engineering standard procedure or medical experimental protocol [6, 7, 14]. For in-vitro tests, samples are usually excised from the main body either dead animals or human corpse. For example, samples are excised from the skin of human corpses donated for science and research purposes [7]. Another example involved samples from human corpse's skin where death with suffering diabetes deceases [31].

Recently, computational analyses and finite element (FE) simulations are becoming popular tools employed to simulate or analysed complex problems [32-34]. In addition, modern technologies involving computer-electronic integration such as digital image, Dynamics Optical Coheren Elastography (OCE), Laser and High Frequancy Ultrasonic (LUS) has also emerged and employed.

Based on literatures reviewed and discussed [1-34], consideration and strategies are outlined in this tudy to enhance research and further analyse the behaviour of bovine skin in order to enhance knowledge about skin mechanical behaviour. For the first time, this paper reveals the methodology and combination of results obtained from experiments, theoretical and statistical analyses and computer simulation pertaining to the biomechanical study of bovine skin. The ultimate goal of this research is to quantify the biomechanical properties of skin. The significance of having this characteristic could offer a detail scientific information and data in modelling skin behaviour for engineering application, medical practice or computer animation. The accuracy, reliability and reproducibility of the data have been measured and proven to be good.

2.0 METHODOLOGY

The research methodology for this study comprises of three main approaches:

- Experiments (Tensile tests)
- Numerical Analyses (theoretical study and statistical analysis)
- Simulation using commercial software

2.1 Experimental Procedure

In general, the experimental approach underwent several stages. Stage 1 refers to the sample preparation, Stage 2 refers to material testing and Stage 3 refers to analysis and results interpretation.

2.1.1 Stage 1: Sample Preparation

30 specimens were prepared from fresh slaughtered bovine. Information and data taken showed that the male bovine, age 24 months, was normal and healthy. For testing purposes, the skin was thoroughly examined to ensure that the specimens have no sign of injury and defect (skin diseases or scars). The specimens were excised at the butt-bend region. The skin parts and layout are illustrated in Table 1 part names (nomenclature)and Figure 1 respectively. The position of butt-bend (g and f) on bovine skin is labeled in Figure 1.

Table 1 Nomenclature of bovine skin

Position	Parts
a	Cheek
b	Face
c	Shoulder
d	Fore Shank
e	Belly
f	Bend
g	Butt
h	Belly Middle
i	Hind Shank

All samples were excised manually using surgical scalpels and segmented utility knife. As there is yet a standard testing procedure for animal skin, an international standard testing procedure for leather is adopted (ASTM D2209-00). To ensure a perfect and accurate cutting edge and dimension, a mould or template of I-shape (dogbone) was prepared from corrugated plastic cardboard (blue color) and shown in Figure 2(a). The exact dimension of I-shape was printed on paper and paste on plastic cardboard to get the perfect size as required by the ASTM D2209-00. The ready template is shown in Figure 2(b), where the bovine skin were then excised precisely according to the mould shape. All fat and meat are completely removed to ensure a constant skin thickness throughout the testing. The overall size of I-shape excise was 171mm x 31.8mm for length and width respectively.

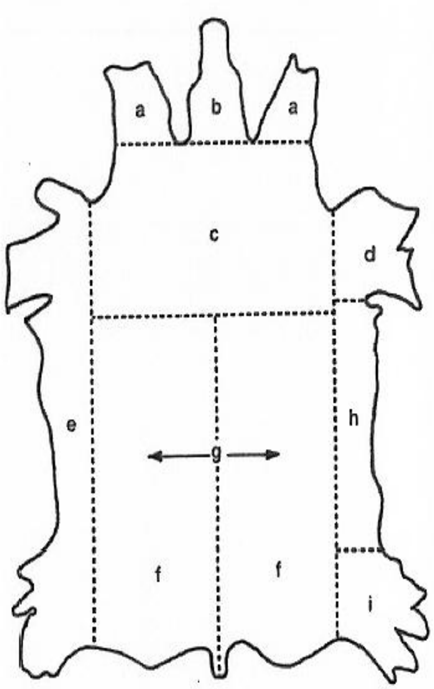
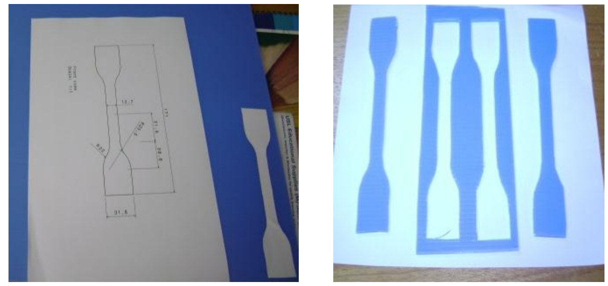


Figure 1 Bovine skin layout

2.1.2 Stage 2: In-Vitro Study (Mechanical Testing)

During uniaxial testing performed, the deformation of the samples are observed. This in-vitro investigation was conducted using the tensile testing machine (Instron Dynatup 9250) located at the Strength of Material Laboratory, Faculty of Mechanical Engineering, UiTM Shah Alam. The maximum load and speed rate applied were 281 N and 200 N/mm respectively. All 30 specimens underwent detail in-vitro observation. Figure 3 and Figure 4 shows specimens before and after mechanical testing respectively. The experimental outputs (mechanical parameters, i.e. displacement, strain and stress) were the important data gathered and recorded. Figure 5 illustrates the 30 tested specimens in this study.



(a) **(b)**

Figure 2 (a) Schematic Drawing; (b) Plastic Mould (Template)

Figure 3 Specimen before testing

2.2 Numerical Analyses and Programming

The main aim of theoretical study, numerical analyses involving Matlab programming in this study was to determine the hyperelastic material parameters such as stretch, Ogden coefficient and Ogden exponent; from the experimental outputs (mechanical parameters, i.e displacement, strain and stress). Moreover, to ensure the accuracy and reliability of the data and outputs generated from in-vitro tests, basic statistical analysis was conducted to evaluate the procedure repeatability and reproducibility. Adding to that, statistical data characteristics such as the distribution graph, skewness, interquartile range (IQR), kurtosis and box plot are also assessed.

For this study, bovine skin was assumed to be hyperelastic and for this purpose, Ogden theory is employed to describe the highly non-linear, anisotropic and hyperelastic behaviour of bovine skin. The basic theory of elasticity was introduced by Ogden [35] and Ogden proposed the strain energy function, W (isotropy and incompressible) as shown in eq (1):

$$W = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i}\left(\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3\right) \qquad \text{(Eq.1)}$$

where λ_i are the principal stretches. μ_i and α_i are the material parameters with the function's order of N. For this study, a single function's order is considered and thus, N =1.

Considering the Ogden model, where the material is assumed to be isotropic, hyperelastic and incompressible; deriving the relation of engineering stress, σ_E and principal stretches, λ, in 1-direction (uniaxial) will yield eq (2) [14].

$$\sigma_E = \frac{\mu}{\lambda}\left(\lambda^{\alpha} - \lambda^{-\alpha/2}\right) \qquad \text{(Eq.2)}$$

Figure 4 Specimen after testing

Main data obtained from experiment (i.e. displacement and engineering stress) were then used to compute stretch. Next, the stress-stretch data were generated and plotted. Based on eq. (2), an a curve fitting procedure was performed to generate Ogden's coefficient value, μ and Ogden's exponent value, α that best match the experiments data. To solve this two unknowns, Least square method was employed based on Microsoft Excel built in function. The determined parameters, μ and α were then used to plot curves comparing both experiments and numerical results. For plotting and comparison, a specific Matlab programme (Matlab ver. R2012a, The MathWorks, Inc.) was written to illustrate the deformation behaviour of bovine skin under uniaxial tension.

The data and outputs from numerical approach (i.e. stretch and the quantified hyperelastic materials parameters, μ and α) were the most important data gathered and recorded for finite element simulation.

2.3 Finite Element (F.E) Simulation

The main aim of the finite element analysis and simulation in this study was replicate the experimental set-up and simulate the deformation behaviour of bovine skin using the data and outputs from experiments (i.e. sample specification, load and boundary condition) and numerical approaches (i.e. the quantified hyperelastic materials parameters, , μ and α). The outputs from the finite element simulation (i.e. simulated displacements and stress contour)are important for comparison, verification and visualization.

For FE modelling and simulation, a commercial finite element software was used (ANSYS v12.1, 2009 SAS IP, Inc.). The skin was modelled exactly to the geometry of dogbone shape according to specimen tested (ASTM D2209-00). The specimens were meshed into 4 x 20 (Model 1) and 8 x 37 (Model 2) using 3D solid 20-noded elements respectively. One end of the specimen was fixed and uniaxial load was applied up to testing requirement. Ogden materials with single order, N = 1, was selected and the value of μ and α quantified from the numerical approach was input into the FE model.

Finally, the outputs from the FE simulation (i.e. contour and values of simulated displacements and stresses) were used to compare with the experimental results (i.e. load-displacement data) and numerical results (i.e. stress-stretch data. Apart from that, the graphical representation (i.e. deformed samples) has provided visualization for better understanding.

Figure 5 30 tested specimens

3.0 RESULTS AND DISCUSSION

3.1 In-Vitro Results

The experiments which was conducted according to ASTM D2209-00; has generated outputs and data related to mechanical parameters (i.e. displacement, strain and stress). Figure 6 illustrates the in-vitro test outputs for the specimens. The stress-stretch graphs are plotted for the 30 specimens respectively. From the uniaxial tests, the minimum and maximum tensile stresses recorded were 2.412 MPa and 2.987 MPa respectively. The average modulus of elasticity of 30 specimens was found to be 12.57 MPa. As seen in Figure 4 and Figure 5, it is obvious that once the specimen was tested, it cannot be re-test even though the skin are not fail or break. Elongation and strain were computed for every specimen during the in-vitro tests and compared to mean value; and it could be observed in Figure 6 that the computed maximum elongation compared to the mean value was found to be 104.74% (specimen 7). The minimum specimen elongation compared to the mean value was found to be 35.11% 9 (specimen 3).

All important statistical characteristics were analysed at engineering stress level of 2.4MPa and Table 2 lists the parameters information in details. The value of interquartile range (IQR) and skewness are 0.209 and 0.810. The statistical data allows to furher examine the dispersion of the results and hence proving the reliability of the data generated from experiments. Once the IQR determined, the box plot are plotted to see the data distribution (Figure 7).

Table 2 Statistical characteristic

	Stretch at 2.4MPa
N	30
Minimum	1.226
Maximum	2.316
Mean	1.643
Std. Deviation	0.219
Variance	0.048
Skewness	0.810

3.2 Results from Numerical Analyses

The main aim of theoretical study, numerical analyses involving Matlab programming in this study was to determine the hyperelastic material parameters such as stretch, Ogden coefficient and Ogden exponent; from the experimental outputs (mechanical parameters, i.e displacement, strain and stress) and this has been achieved successfully. Therefore, for this paper for the first time reveals the quantified value of Ogden material parameters (i.e. Ogden coefficient, μ and Ogden exponent, α) and the results are shown in Table 3.

Table 3 Quantified ogden parameters

Ogden Material Parameter	Result
μ	0.017 MPa
α	11.049

When the quantified (numerically) value of Ogden material parameters are plotted into a curve and compared the curve (based on mean value from 30 specimens) generated from experiments (Figure 8), it is apparent that the curve match closely to the experimental data. This proves that the quantified value (i.e. μ = 0.017 MPa and α = 11.049)is valid.

3.3 Results from FE Simulation

Inputting the quantified (numerically) value of Ogden material parameters (μ = 0.017 MPa and α = 11.049) into the FE model, simulation was performed to investigate the difference of results (i.e. deformation) between numerical approach and finite element implementation compared to experiments. A graph (Figure 9) is plotted and the displacement contour for undeformed-deformed FE model is illustrated (Figure 10) for observation and analysis.

Figure 9 depicts the displacement contour (i.e. uniaxial elongation) for two FE models (i.e. FE model 1 consists of 80 and FE model 2 consists of 298 elements) compared to the experimental data. It could be noticed that by increasing the number of elements, the results improved (i.e. closer to experimental results) [30]

The simulated deformation and displacement contour (i.e. uniaxial elongation)of the specimen could be observed as illustrated in Figure 10. The results reflect large deformation and thus, in general this is similar to the actual deformation seen during tensile test.

3.4 Discussion

Compared to previous research [14], the current quantified (numerically) value of Ogden material parameters (i.e. μ = 0.017 MPa and α = 11.049)are slightly lower, nevertheless the values are still in range. One of the strengths of this study is the large number of sample (30 specimen tested) to ensure that the results are more reliable and accurate for further analysis. Referring to Figure 6, it is obvious that only few (less than 5 specimens)data offset far from the mean value. By observation, most of the curves concentrated near to the mean value. By statistics (Table 2), the variance was found to be less than 5%, which proves that experiments have generated reliable result.

Based on statistical characteristics tabulated in Table 2 and graphs shown in Figure 7, the distribution pattern is observed to be positive skew. This is also clearly illustrated by box plot and bell shape of a normal distribution graph.

Furthermore, from this study, a new procedure for curve fitting using Microsoft Excel built in function employed to determine the Ogden material parameters is found useful and easier new compared to previous study [14]. It shortens the processing time significantly in determining the accurate value μ and α directly compared to manual iteration. The result (i.e. the numerically quantified value of μ and α) is good and this is proven as clearly shown in Figure 8.

For simulation, the results for the two FE models (i.e. FE model 1 consists of 80 elements and FE model 2 consists of 298 elements do not show much difference (Figure 9). Eventhough the number of element and node increases significantly, the results only improved by 4.79% (calculated from results obtained from respective interested node location). In general, the smallest gap between the FE simulation results compared to experiments is found to be 34.50% (i.e. the difference at reference position 7 between FE model 2 and experiments). This might due to the incapability of the elements to deform excessively and highly non-linear (i.e. the limitation of the FE elements and computation to simulate large deformation behavior).

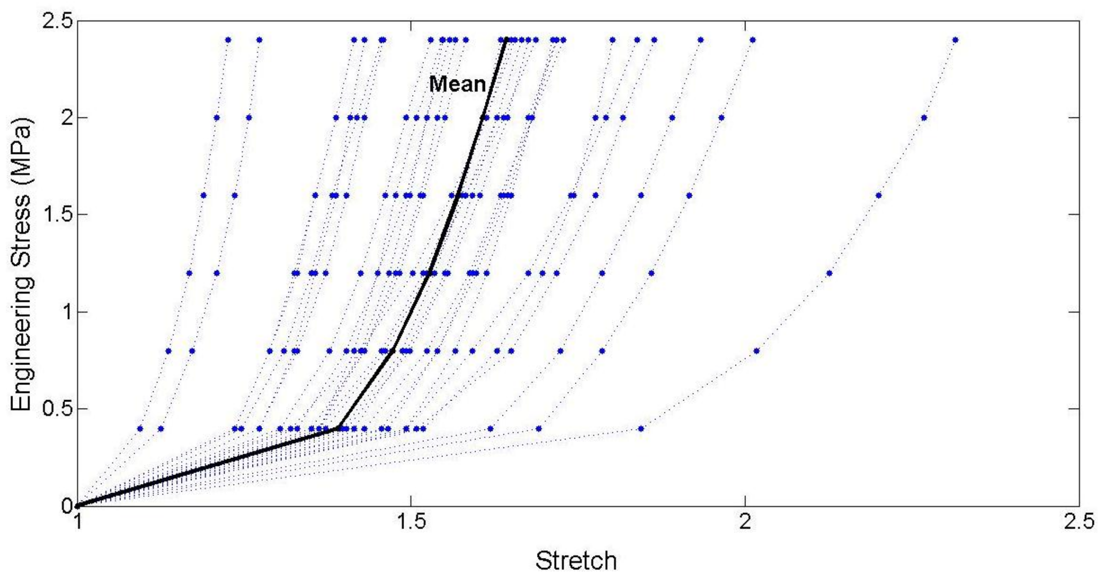


Figure 6 Stress-stretch curves for 30 specimen

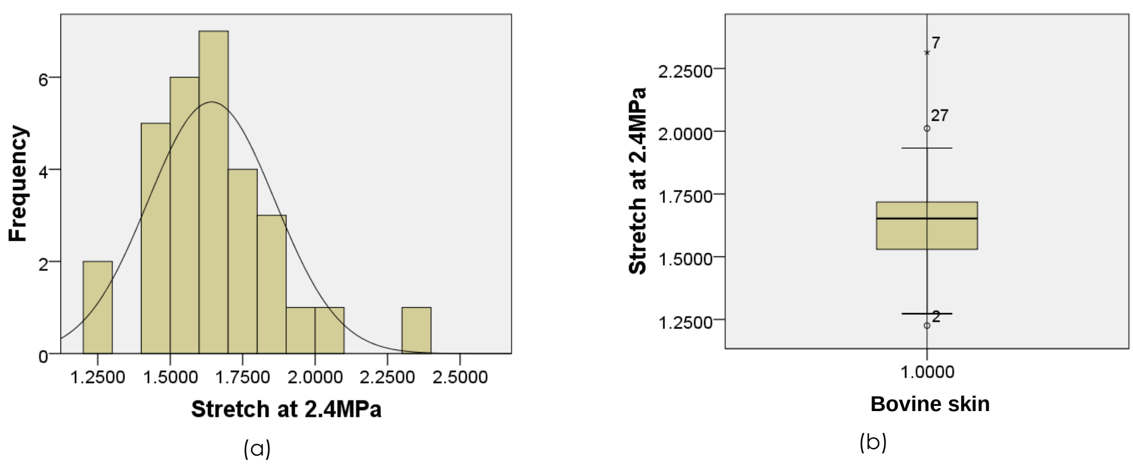


Figure 7 Statistical graph at stress 2.4 MPa (a) Histogram; (b) Box plot

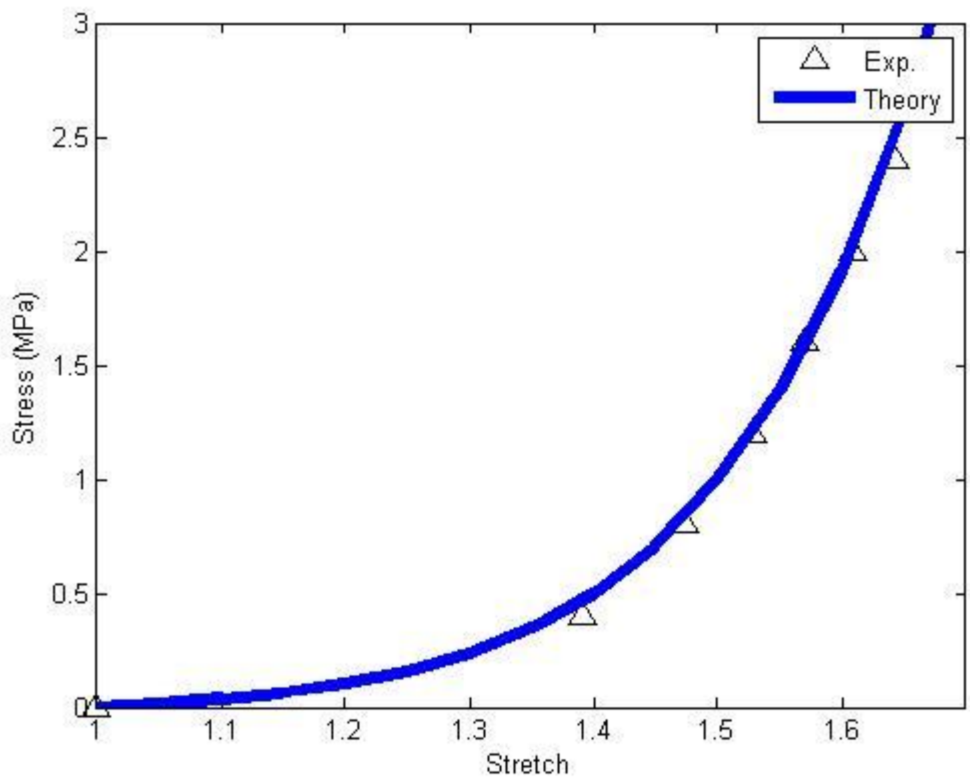


Figure 8 Numerical results compared to experimental results

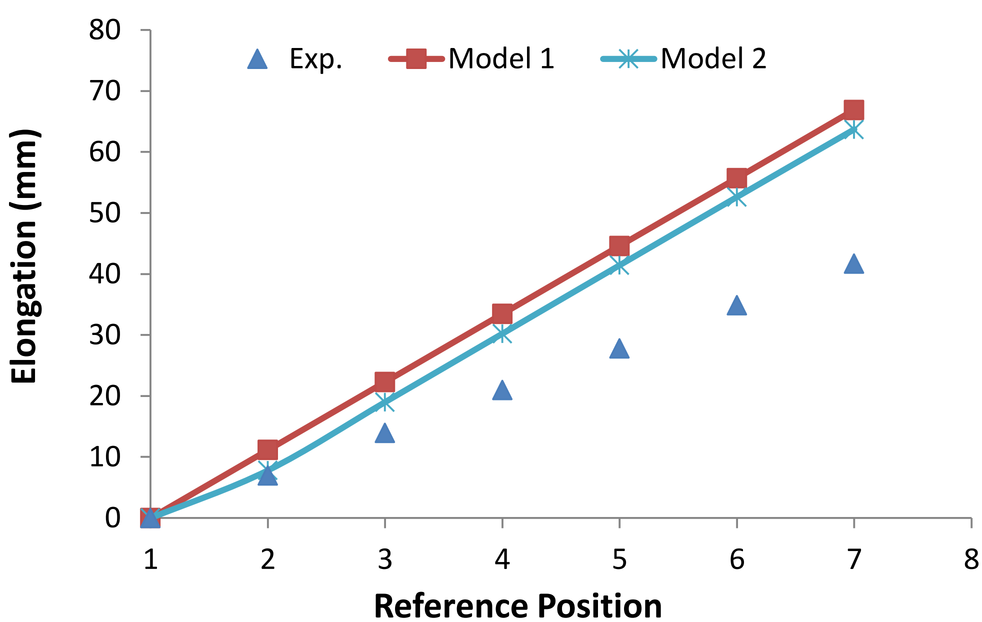


Figure 9 Simulated results compared to experiment

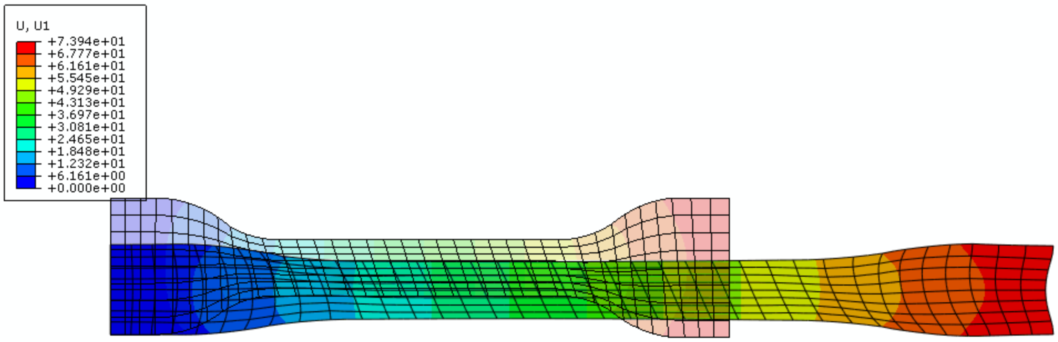


Figure 10 Simulated deformation and displacement contour (uniaxial elongation)

4.0 CONCLUSION

This paper reports the experimental approach, theoretical study, numerical analyses involving Matlab programming and finite element simulation to investigate and simulate bovine skin deformation and biomechanical behaviour.

The main objective of this study is to quantify the hyperelastic material parameters from the experimental outputs; and the results obtained (i.e. μ = 0.017 MPa and α = 11.049) proves that this has been achieved successfully. Comparing the results from the numerical approach and finite element to the experimental data has highlighted the advantages and limitation of each approach. Numerical approach has generated good results via easier procedure, however finite element simulation offers graphical visualisation for better undertanding. The success to generate data and results from different approaches (experiments, numerical analysis and finite element simulation) has opened up wider perspectives and provided alternative solutions for future analysis and problem solving. It is important to conduct further research and analysis to improve the results. Nevertheless, it is undeniable that the current study is significant and has contributed to enhancing knowledge about skin mechanical behaviour.

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